Cosmoparticle Physics - the Challenge for the Millenium

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Abstract. Cosmoparticle physics is the natural result of development of mutual relationship between cosmology and particle physics. Its prospects offer the way to study the theory of everything and the true history of the Universe, based on it, in the proper combination of their indirect physical, astrophysical and cosmological signatures. We may be near the first positive results in this direction. The basic ideas of cosmoparticle physics are briefly reviewed.

Cosmoparticle physics originates from the well established relationship between microscopic and macroscopic descriptions in theoretical physics. Remind the links between statistical physics and thermodynamics, or between electrodynamics and theory of electron. To the end of the XX Century the new level of this relationship was realized. It followed both from the cosmological necessity to go beyond the world of known elementary particles in the physical grounds for inflationary cosmology with baryosynthesis and dark matter as well as from the necessity for particle theory to use cosmological tests as the important and in many cases unique way to probe its predictions.

The convergence of the frontiers of our knowledge in micro- and macro worlds leads to the wrong circle of problems, illustrated by the mystical Uhroboros (self-eating-snake). The Uhroboros puzzle may be formulated as follows: *The theory of the Universe is based on the predictions of particle theory, that need cosmology for their test.* Cosmoparticle physics [1], [2], [3] offers the way our of this wrong circle. It studies the fundamental basis and mutual relationship between micro-and macro-worlds in the proper combination of physical, astrophysical and cosmological signatures.

Let's specify in more details the set of links between fundamental particle properties and their cosmological effects.

The role of particle content in the Einstein equations is reduced to its contribution into energy-momentum tensor. So, the set of relativistic species, dominating in the Universe, realizes the relativistic equation of state $p = \varepsilon/3$ and the relativistic stage of expansion. The difference between relativistic bosons and fermions or various bosonic (or fermionic) species is accounted by the statistic weight of respective degree of freedom. The very treatment of different species of particles as equivalent degrees of freedom physically assumes strict symmetry between them.

Such strict symmetry is not realized in Nature. There is no exact symmetry between bosons and fermions (e.g. supersymmetry). There is no exact symme-

try between various quarks and leptons. The symmetry breaking implies the difference in particle masses. The particle mass pattern reflects the hierarchy of symmetry breaking.

Noether's theorem relates the exact symmetry to conservation of respective charge. The lightest particle, bearing the strictly conserved charge, is absolutely stable. So, electron is absolutely stable, what reflects the conservation of electric charge. In the same manner the stability of proton is conditioned by the conservation of baryon charge. The stability of ordinary matter is thus protected by the conservation of electric and baryon charges, and its properties reflect the fundamental physical scales of electroweak and strong interactions. Indeed, the mass of electron is related to the scale of the electroweak symmetry breaking, whereas the mass of proton reflects the scale of QCD confinement.

Extensions of the standard model imply new symmetries and new particle states. The respective symmetry breaking induces new fundamental physical scales in particle theory. If the symmetry is strict, its existence implies new conserved charge. The lightest particle, bearing this charge, is stable. The set of new fundamental particles, corresponding to the new strict symmetry, is then reflected in the existence of new stable particles, which should be present in the Universe and taken into account in the total energy-momentum tensor.

Most of the known particles are unstable. For a particle with the mass m the particle physics time scale is $t \sim 1/m$, so in particle world we refer to particles with lifetime $\tau \gg 1/m$ as to metastable. To be of cosmological significance metastable particle should survive after the temperature of the Universe T fell down below $T \sim m$, what means that the particle lifetime should exceed $t \sim (m_{Pl}/m) \cdot (1/m)$. Such a long lifetime should find reason in the existence of an (approximate) symmetry. From this viewpoint, cosmology is sensitive to the most fundamental properties of microworld, to the conservation laws reflecting strict or nearly strict symmetries of particle theory.

However, the mechanism of particle symmetry breaking can also have the cosmological impact. Heating of condensed matter leads to restoration of its symmetry. When the heated matter cools down, phase transition to the phase of broken symmetry takes place. In the course of the phase transitions, corresponding to given type of symmetry breaking, topological defects can form. One can directly observe formation of such defects in liquid crystals or in superfluids. In the same manner the mechanism of spontaneous breaking of particle symmetry implies restoration of the underlying symmetry. When temperature decreases in the course of cosmological expansion, transitions to the phase of broken symmetry can lead, depending on the symmetry breaking pattern, to formation of topological defects in very early Universe. The defects can represent the new form of stable particles (as it is in the case of magnetic monopoles), or the form of extended structures, such as cosmic strings or cosmic walls.

In the old Big bang scenario the cosmological expansion and its initial conditions was given *a priori*. In the modern cosmology the expansion of the Universe and its initial conditions is related to the process of inflation. The global properties of the Universe as well as the origin of its large scale structure are the result

of this process. The matter content of the modern Universe is also originated from the physical processes: the baryon density is the result of baryosynthesis and the nonbaryonic dark matter represents the relic species of physics of the hidden sector of particle theory. Physics, underlying inflation, baryosynthesis and dark matter, is referred to the extensions of the standard model, and the variety of such extensions makes the whole picture in general ambiguous. However, in the framework of each particular physical realization of inflationary model with baryosynthesis and dark matter the corresponding model dependent cosmological scenario can be specified in all the details. In such scenario the main stages of cosmological evolution, the structure and the physical content of the Universe reflect the structure of the underlying physical model. The latter should include with necessity the standard model, describing the properties of baryonic matter, and its extensions, responsible for inflation, baryosynthesis and dark matter. In no case the cosmological impact of such extensions is reduced to reproduction of these three phenomena only. The nontrivial path of cosmological evolution, specific for each particular realization of inflational model with baryosynthesis and nonbaryonic dark matter, always contains some additional model dependent cosmologically viable predictions, which can be confronted with astrophysical data. The part of cosmoparticle physics, called cosmoarcheology, offers the set of methods and tools probing such predictions.

Cosmoarcheology considers the results of observational cosmology as the sample of the experimental data on the possible existence and features of hypothetical phenomena predicted by particle theory. To undertake the *Gedanken Experiment* with these phenomena some theoretical framework to treat their origin and evolution in the Universe should be assumed. As it was pointed out in [4] the choice of such framework is a nontrivial problem in the modern cosmology.

Indeed, in the old Big bang scenario any new phenomenon, predicted by particle theory was considered in the course of the thermal history of the Universe, starting from Planck times. The problem is that the bedrock of the modern cosmology, namely, inflation, baryosynthesis and dark matter, is also based on experimentally unproven part of particle theory, so that the test for possible effects of new physics is accomplished by the necessity to choose the physical basis for such test. There are two possible solutions for this problem: a) a crude model independent comparison of the predicted effect with the observational data and b) the model dependent treatment of considered effect, provided that the model, predicting it, contains physical mechanism of inflation, baryosynthesis and dark matter.

The basis for the approach (a) is that whatever happened in the early Universe its results should not contradict the observed properties of the modern Universe. The set of observational data and, especially, the light element abundance and thermal spectrum of microwave background radiation put severe constraint on the deviation from thermal evolution after 1 s of expansion, what strengthens the model independent conjectures of approach (a).

One can specify the new phenomena by their net contribution into the cosmological density and by forms of their possible influence on parameters of matter

and radiation. In the first aspect we can consider strong and weak phenomena. Strong phenomena can put dominant contribution into the density of the Universe, thus defining the dynamics of expansion in that period, whereas the contribution of weak phenomena into the total density is always subdominant. The phenomena are time dependent, being characterized by their time-scale, so that permanent (stable) and temporary (unstable) phenomena can take place. They can have homogeneous and inhomogeneous distribution in space. The amplitude of density fluctuations $\delta \equiv \delta\varrho/\varrho$ measures the level of inhomogeneity relative to the total density, ϱ. The partial amplitude $\delta_i \equiv \delta\varrho_i/\varrho_i$ measures the level of fluctuations within a particular component with density ϱ_i, contributing into the total density $\varrho = \sum_i \varrho_i$. The case $\delta_i \geq 1$ within the considered i-th component corresponds to its strong inhomogeneity. Strong inhomogeneity is compatible with the smallness of total density fluctuations, if the contribution of inhomogeneous component into the total density is small: $\varrho_i \ll \varrho$, so that $\delta \ll 1$.

The phenomena can influence the properties of matter and radiation either indirectly, say, changing of the cosmological equation of state, or via direct interaction with matter and radiation. In the first case only strong phenomena are relevant, in the second case even weak phenomena are accessible to observational data. The detailed analysis of sensitivity of cosmological data to various phenomena of new physics are presented in [3].

The basis for the approach (b) is provided by a particle model, in which inflation, baryosynthesis and nonbaryonic dark matter is reproduced. Any realization of such physically complete basis for models of the modern cosmology contains with necessity additional model dependent predictions, accessible to cosmoarcheological means. Here the scenario should contain all the details, specific to the considered model, and the confrontation with the observational data should be undertaken in its framework. In this approach complete cosmoparticle physics models may be realized, where all the parameters of particle model can be fixed from the set of astrophysical, cosmological and physical constraints. Even the details, related to cosmologically irrelevant predictions, such as the parameters of unstable particles, can find the cosmologically important meaning in these models. So, in the model of horizontal unification [5], [6], [7], the top quark or B-meson physics fixes the parameters, describing the dark matter, forming the large scale structure of the Universe.

To study the imprints of new physics in astrophysical data cosmoarcheology implies the forms and means in which new physics leaves such imprints. So, the important tool of cosmoarcheology in linking the cosmological predictions of particle theory to observational data is the *Cosmophenomenology* of new physics. It studies the possible hypothetical forms of new physics, which may appear as cosmological consequences of particle theory, and their properties, which can result in observable effects.

The simplest primordial form of new physics is the gas of new stable massive particles, originated from early Universe. For particles with the mass m, at high temperature $T > m$ the equilibrium condition, $n \cdot \sigma v \cdot t > 1$ is valid, if their

annihilation cross section $\sigma > 1/(mm_{Pl})$ is sufficiently large to establish the equilibrium. At $T < m$ such particles go out of equilibrium and their relative concentration freezes out. More weakly interacting species decouple from plasma and radiation at $T > m$, when $n \cdot \sigma v \cdot t \sim 1$, i.e. at $T_{dec} \sim (\sigma m_{Pl})^{-1}$. The maximal temperature, which is reached in inflationary Universe, is the reheating temperature, T_r, after inflation. So, the very weakly interacting particles with the annihilation cross section $\sigma < 1/(T_r m_{Pl})$, as well as very heavy particles with the mass $m \gg T_r$ can not be in thermal equilibrium, and the detailed mechanism of their production should be considered to calculate their primordial abundance.

Decaying particles with the lifetime τ, exceeding the age of the Universe, t_U, $\tau > t_U$, can be treated as stable. By definition, primordial stable particles survive to the present time and should be present in the modern Universe. The net effect of their existence is given by their contribution into the total cosmological density. They can dominate in the total density being the dominant form of cosmological dark matter, or they can represent its subdominant fraction. In the latter case more detailed analysis of their distribution in space, of their condensation in galaxies, of their capture by stars, Sun and Earth, as well as of the effects of their interaction with matter and of their annihilation provides more sensitive probes for their existence. In particular, hypothetical stable neutrinos of the 4th generation with the mass about 50 GeV are predicted to form the subdominant form of the modern dark matter, contributing less than 0,1 % to the total density. However, direct experimental search for cosmic fluxes of weakly interacting massive particles (WIMPs) may be sensitive to the existence of such component [8], [9], and may be even favors it [9]. It was shown in [10], [11], [12] that annihilation of 4th neutrinos and their antineutrinos in the Galaxy can explain the galactic gamma-background, measured by EGRET in the range above 1 GeV, and that it can give some clue to explanation of cosmic positron anomaly, claimed to be found by HEAT. 4th neutrino annihilation inside the Earth should lead to the flux of underground monochromatic neutrinos of known types, which can be traced in the analysis of the already existing and future data of underground neutrino detectors [12].

New particles with electric charge and/or strong interaction can form anomalous atoms and contain in the ordinary matter as anomalous isotopes. For example, if the lightest quark of 4th generation is stable, it can form stable charged hadrons, serving as nuclei of anomalous atoms of e.g. crazy helium [13].

Primordial unstable particles with the lifetime, less than the age of the Universe, $\tau < t_U$, can not survive to the present time. But, if their lifetime is sufficiently large to satisfy the condition $\tau \gg (m_{Pl}/m) \cdot (1/m)$, their existence in early Universe can lead to direct or indirect traces. Cosmological flux of decay products contributing into the cosmic and gamma ray backgrounds represents the direct trace of unstable particles. If the decay products do not survive to the present time their interaction with matter and radiation can cause indirect trace in the light element abundance or in the fluctuations of thermal radiation. If the particle lifetime is much less than 1s the multi-step indirect traces are possible, provided that particles dominate in the Universe before their de-

cay. On the dust-like stage of their dominance black hole formation takes place, and the spectrum of such primordial black holes traces the particle properties (mass, frozen concentration, lifetime) [14]. The particle decay in the end of dust like stage influences the baryon asymmetry of the Universe. In any way cosmophenomenoLOGICAL chains link the predicted properties of even unstable new particles to the effects accessible in astronomical observations. Such effects may be important in the analysis of the observational data.

So, the only direct evidence for the accelerated expansion of the modern Universe comes from the distant SN I data. The data on the cosmic microwave background (CMB) radiation and large scale structure (LSS) evolution (see e.g. [15]) prove in fact the existence of homogeneously distributed dark energy and the slowing down of LSS evolution at $z \leq 3$. Homogeneous negative pressure medium (Λ-term or quintessence) leads to *relative* slowing down of LSS evolution due to acceleration of cosmological expansion. However, both homogeneous component of dark matter and slowing down of LSS evolution naturally follow from the models of Unstable Dark Matter (UDM) (see [3] for review), in which the structure is formed by unstable weakly interacting particles. The weakly interacting decay products are distributed homogeneously. The loss of the most part of dark matter after decay slows down the LSS evolution. The dominantly invisible decay products can contain small ionizing component [6]. Thus, UDM effects will deserve attention, even if the accelerated expansion is proved.

The parameters of new stable and metastable particles are also determined by the pattern of particle symmetry breaking. This pattern is reflected in the succession of phase transitions in the early Universe. The phase transitions of the first order proceed through the bubble nucleation, which can result in black hole formation. The phase transitions of the second order can lead to formation of topological defects, such as walls, string or monopoles. The observational data put severe constraints on magnetic monopole and cosmic wall production, as well as on the parameters of cosmic strings. The succession of phase transitions can change the structure of cosmological defects. The more complicated forms, such as walls-surrounded-by-strings can appear. Such structures can be unstable, but their existence can lead the trace in the nonhomogeneous distribution of dark matter and in large scale correlations in the nonhomogeneous dark matter structures, such as *archioles* [16]. The large scale correlations in topological defects and their imprints in primordial inhomogeneities is the indirect effect of inflation, if phase transitions take place after reheating of the Universe. Inflation provides in this case the equal conditions of phase transition, taking place in causally disconnected regions.

If the phase transitions take place on inflational stage new forms of primordial large scale correlations appear. The example of global U(1) symmetry, broken spontaneously in the period of inflation and successively broken explicitly after reheating, was recently considered in [17]. In this model, spontaneous U(1) symmetry breaking at inflational stage is induced by the vacuum expectation value $\langle\psi\rangle = f$ of a complex scalar field $\Psi = \psi \exp{(\mathrm{i}\theta)}$, having also explicit symmetry breaking term in its potential $V_{eb} = \Lambda^4(1 - \cos\theta)$. The latter is negligible in the

period of inflation, if $f \gg \Lambda$, so that there appears a valley relative to values of phase in the field potential in this period. Fluctuations of the phase θ along this valley, being of the order of $\Delta\theta \sim H/(2\pi f)$ (here H is the Hubble parameter at inflational stage) change in the course of inflation its initial value within the regions of smaller size. Owing to such fluctuations, for the fixed value of θ_{60} in the period of inflation with *e-folding* $N = 60$ corresponding to the part of the Universe within the modern cosmological horizon, strong deviations from this value appear at smaller scales, corresponding to later periods of inflation with $N < 60$. If $\theta_{60} < \pi$, the fluctuations can move the value of θ_N to $\theta_N > \pi$ in some regions of the Universe. After reheating, when the Universe cools down to temperature $T = \Lambda$ the phase transition to the true vacuum states, corresponding to the minima of V_{eb} takes place. For $\theta_N < \pi$ the minimum of V_{eb} is reached at $\theta_{vac} = 0$, whereas in the regions with $\theta_N > \pi$ the true vacuum state corresponds to $\theta_{vac} = 2\pi$. For $\theta_{60} < \pi$ in the bulk of the volume within the modern cosmological horizon $\theta_{vac} = 0$. However, within this volume there appear regions with $\theta_{vac} = 2\pi$. These regions are surrounded by massive domain walls, formed at the border between the two vacua. Since regions with $\theta_{vac} = 2\pi$ are confined, the domain walls are closed. After their size equals the horizon, closed walls can collapse into black holes. The minimal mass of such black hole is determined by the condition that it's Schwarzschild radius, $r_g = 2GM/c^2$ exceeds the width of the wall, $l \sim f/\Lambda^2$, and it is given by $M_{min} \sim f(m_{Pl}/\Lambda)^2$. The maximal mass is determined by the mass of the wall, corresponding to the earliest region $\theta_N > \pi$, appeared at inflational stage. This mechanism can lead to formation of primordial black holes of a whatever large mass (up to the mass of AGNs [18]). Such black holes appear in the form of primordial black hole clusters, exhibiting fractal distribution in space [17]. It can shed new light on the problem of galaxy formation.

Primordial strong inhomogeneities can also appear in the baryon charge distribution. The appearance of antibaryon domains in the baryon asymmetrical Universe, reflecting the inhomogeneity of baryosynthesis, is the profound signature of such strong inhomogeneity [19]. On the example of the model of spontaneous baryosynthesis (see [23] for review) the possibility for existence of antimatter domains, surviving to the present time in inflationary Universe with inhomogeneous baryosynthesis was revealed in [24]. Evolution of sufficiently dense antimatter domains can lead to formation of antimatter globular clusters [25]. The existence of such cluster in the halo of our Galaxy should lead to the pollution of the galactic halo by antiprotons. Their annihilation can reproduce [26] the observed galactic gamma background in the range tens-hundreds MeV. The prediction of antihelium component of cosmic rays [27], accessible to future searches for cosmic ray antinuclei in PAMELA and AMS II experiments, as well as of antimatter meteorites [28] provides the direct experimental test for this hypothesis.

So the primordial strong inhomogeneities in the distribution of total, dark matter and baryon density in the Universe is the new important phenomenon

of cosmological models, based on particle models with hierarchy of symmetry breaking.

The new physics follows from the necessity to extend the Standard model. The white spots in the representations of symmetry groups, considered in the extensions of the Standard model, correspond to new unknown particles. The extension of the symmetry of gauge group puts into consideration new gauge fields, mediating new interactions. Global symmetry breaking results in the existence of Goldstone boson fields.

For a long time the necessity to extend the Standard model had purely theoretical reasons. Aesthetically, because full unification is not achieved in the Standard model; practically, because it contains some internal inconsistencies. It does not seem complete for cosmology. One has to go beyond the Standard model to explain inflation, baryosynthesis and nonbaryonic dark matter. Recently there has appeared a set of experimental evidences for the existence of neutrino oscillations (see for recent review e.g. [20], [21], [22]), of cosmic WIMPs [9], and of double neutrinoless beta decay [29]. Whatever is the accepted status of these evidences, they indicate that the experimental searches may have already crossed the border of new physics.

In particle physics direct experimental probes for the predictions of particle theory are most attractive. The predictions of new charged particles, such as supersymmetric particles or quarks and leptons of new generation, are accessible to experimental search at accelerators of new generation, if their masses are in 100GeV-1TeV range. However, the predictions related to higher energy scale need non-accelerator or indirect means for their test.

The search for rare processes, such as proton decay, neutrino oscillations, neutrinoless beta decay, precise measurements of parameters of known particles, experimental searches for dark matter represent the widely known forms of such means. Cosmoparticle physics offers the nontrivial extensions of indirect and non-accelerator searches for new physics and its possible properties. In experimental cosmoarcheology the data is to be obtained, necessary to link the cosmophenomenology of new physics with astrophysical observations (See [4]). In experimental cosmoparticle physics the parameters, fixed from the consitency of cosmological models and observations, define the level, at which the new types of particle processes should be searched for (see [30]).

The theories of everything should provide the complete physical basis for cosmology. The problem is that the string theory [31] is now in the form of "theoretical theory", for which the experimental probes are widely doubted to exist. The development of cosmoparticle physics can remove these doubts. In its framework there are two directions to approach the test of theories of everything.

One of them is related with the search for the experimentally accessible effects of heterotic string phenomenology. The mechanism of compactification and symmetry breaking leads to the prediction of homotopically stable objects [32] and shadow matter [33], accessible to cosmoarcheological means of cosmoparticle physics. The condition to reproduce the Standard model naturally leads in the heterotic string phenomenology to the prediction of fourth generation of quarks

and leptons [34] with a stable massive 4th neutrino [10], what can be the subject of complete experimental test in the near future. The comparison between the rank of the unifying group E_6 ($r = 6$) and the rank of the Standard model ($r = 4$) implies the existence of new conserved charges and new (possibly strict) gauge symmetries. New strict gauge U(1) symmetry (similar to U(1) symmetry of electrodynamics) is possible, if it is ascribed to the fermions of 4th generation. This hypothesis explains the difference between the three known types of neutrinos and neutrino of 4th generation. The latter possesses new gauge charge and, being Dirac particle, can not have small Majorana mass due to sea saw mechanism. If the 4th neutrino is the lightest particle of the 4th quark-lepton family, strict conservation of the new charge makes massive 4th neutrino to be absolutely stable. Following this hypothesis [34] quarks and leptons of 4th generation are the source of new long range interaction (y-electromagnetism), similar to the electromagnetic interaction of ordinary charged particles. New strictly conserved local U(1) gauge symmetries can also arise in the development of D-brane phenomenology [35], [36]. If proved, the practical importance of this property could be hardly overestimated.

It is interesting, that heterotic string phenomenology embeds even in its simplest realisation both supersymmetric particles and the 4th family of quarks and leptons, in particular, the two types of WIMP candidates: neutralinos and massive stable 4th neutrinos. So in the framework of this phenomenology the multicomponent analysis of WIMP effects is favorable.

In the above approach some particular phenomenological features of simplest variants of string theory are studied. The other direction is to elaborate the extensive phenomenology of theories of everything by adding to the symmetry of the Standard model the (broken) symmetries, which have serious reasons to exist. The existence of (broken) symmetry between quark-lepton families, the necessity in the solution of strong CP-violation problem with the use of broken Peccei-Quinn symmetry, as well as the practical necessity in supersymmetry to eliminate the quadratic divergence of Higgs boson mass in electroweak theory is the example of appealing additions to the symmetry of the Standard model. The horizontal unification and its cosmology represent the first step on this way, illustrating the approach of cosmoparticle physics to the elaboration of the proper phenomenology for theories of everything [7].

We can conclude that from the very beginning to the modern stage, the evolution of Universe is governed by the forms of matter, different from those we are built of and observe around us. From the very beginning to the present time, the evolution of the Universe was governed by physical laws, which we still don't know. Observational cosmology offers strong evidences favoring the existence of processes, determined by new physics, and the experimental physics approaches to their investigation.

Cosmoparticle physics [1] [2], studying the physical, astrophysical and cosmological impact of new laws of Nature, explores the new forms of matter and their physical properties, what opens the way to use the corresponding new sources

of energy and new means of energy transfer. It offers the great challenge for the new Millennium.

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